

# Magnetic jet model for GRBs and the delayed arrival of $>100$ MeV photons

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## ABSTRACT

Photons of energy larger than 100 MeV from long-GRBs arrive a few seconds after  $< 10$  MeV photons do. We show that this delay is a natural consequence of a magnetic dominated relativistic jet. The much slower acceleration of a magnetic jet with radius (compared with a hot baryonic outflow) results in high energy gamma-ray photons to be converted to electron-positron pairs out to a larger radius whereas lower energy gamma-rays of energy less than  $\sim 10$  MeV can escape when the jet crosses the Thomson-photosphere. The resulting delay for the arrival of high energy photons is found to be similar to the value observed by the Fermi satellite for a number of GRBs. A prediction of this model is that the delay should increase with photon energy ( $E$ ) as  $\sim E^{0.17}$  for  $E > 100$  MeV. The delay depends almost linearly on burst redshift, and on the distance from the central compact object where the jet is launched ( $R_0$ ). Therefore, the delay in arrival of  $>10^2$  MeV photons can be used to estimate burst redshift if the magnetic jet model for gamma-ray generation is correct and  $R_0$  is roughly the same for long-GRBs.

**Key words:** radiation mechanisms: non-thermal - methods: analytical - gamma-rays: bursts, theory

## 1 INTRODUCTION

The Fermi satellite has detected 17 GRBs with photons of energy  $>100$  MeV in the first 3 years of operation. The high energy  $\gamma$ -ray radiation for most of these bursts detected by the LAT (Large Area Telescope) instrument aboard the Fermi satellite shows two interesting features (Omodei et al. 2009): (1) The first  $>100$  MeV photon arrives later than the first lower energy photon ( $\lesssim 1$  MeV) detected by the GBM (Gamma-ray Burst Monitor) – Abdo et al. 2009a,b, 2010, Ackermann et al. 2010 & 2011 (2)  $>100$  MeV radiation lasts for a much longer time compared to the burst duration in the sub-MeV band (Abdo et al. 2009a, 2010).

It is natural to expect radiation lasting for a time duration longer than the prompt GRB burst duration when it is produced in the external shock; external shock results when relativistic ejecta from a GRB runs into the surrounding medium. In fact the Fermi/LAT data ( $>10^2$  MeV) — after the prompt GRB phase, i.e.  $t \gtrsim 30$  s — is found to be consistent with the expectation of the external shock model both in regards to the absolute value of the flux at 100 MeV and its temporal evolution (Kumar & Barniol Duran, 2009, 2010). Moreover, the external shock model provides an excellent fit for the entire observed data — high-energy  $\gamma$ -rays, x-ray, optical and radio frequencies — in the time interval of  $\sim 30$  s and a week (Kumar & Barniol Duran, 2010). These agreements between

the data and the theoretical model provide a compelling case that the observed Fermi/LAT photons for  $t \gtrsim 30$  s originate in the external shock. However, the external shock model encounters a few problems explaining the Fermi/LT data during the prompt phase ( $t \lesssim 30$  s).

The LAT data appears to show short time scale variability — although it is unclear if this is statistically significant considering the relatively small number of photons detected at high energies — which seems to be correlated with the sub-MeV lightcurve. If the lower energy  $\gamma$ -rays detected by Fermi/GBM are produced by a mechanism distinct from the external shock — as suggested by many lines of evidences e.g. Piran (2004), Zhang (2007) — then the implication of this correlation (if real) is that the  $>10^2$  MeV photons generated during the prompt phase might also be produced by the same mechanism.

Another intriguing feature of the data obtained by Fermi is that the spectrum in the energy interval 8 keV – 10 GeV, during the prompt phase, can be fitted with a single Band function for most GRBs<sup>1</sup>. This suggests that photons in the entire Fermi energy band are likely produced by a single mechanism.

A number of mechanisms have been proposed for the generation of high energy photons observed from GRBs such as the photo-

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<sup>1</sup> For three bursts an additional power law component extending from  $\sim 10$  keV to 10 GeV energies is required.

pion, proton synchrotron, inverse-Compton, SSC etc. (see Gupta & Zhang, 2007, Fan & Piran, 2008 for recent reviews). A number of proposals have been put forward to explain the observed delay between the Fermi/LAT and GBM lightcurves, eg. external shock (Kumar & Barniol Duran, 2009; Ghisellini et al. 2010; Ghirlanda et al. 2010; Barniol Duran & Kumar, 2011), proton synchrotron radiation & photo-pion process (Razzaque et al. 2010, Asano et al. 2009), IC scattering of photospheric or cocoon thermal radiation by electrons accelerated in internal shocks (Toma et al. 2009 & 2010) neutron-proton collisions (Beloborodov, 2010; Vurm et al. 2011; Mészáros and Rees, 2011), IC scatterings in internal shocks (Bosnjak et al. 2011).

Whenever higher energy photons are produced at larger radii than lower energy  $\gamma$ -rays we expect a delay for the arrival of high energy photons. Another possible way that a delay could arise is if the radiation is produced while the jet is undergoing acceleration; in this case high energy photons are trapped – converted to  $e^\pm$  – almost until the jet reaches the radius where it attains the terminal Lorentz-factor, whereas lower energy photons are free to escape at the much smaller photospheric radius.

A Poynting jet model for GRBs belongs to this second category, which is discussed in section 2. The application to Fermi GRBs is presented in §3.

## 2 HIGH AND LOW ENERGY PHOTON ARRIVAL TIME FOR A POYNTING JET

The Lorentz factor increases slowly with radius for a magnetic dominated jet; Drenkhahn (2002) finds that  $\Gamma \propto R^{1/3}$  when magnetic field is dissipated via reconnection in a stripped wind and a part of the energy goes into accelerating the jet. The remaining part of the dissipated magnetic field energy is deposited into particles to produce a non-thermal distribution which results in a broad-band synchrotron spectrum extending to multi-GeV energies. Low energy  $\gamma$ -rays can escape the jet when the radiation is produced at a radius that is larger than the Thomson-photospheric radius. However, high energy  $\gamma$ -ray photons can escape only when the jet is at a much larger radius so that the optical depth for  $\gamma$ - $\gamma$  pair production drops below unity. Thus, a Poynting jet model for GRBs offers a straightforward explanation for the delay for the arrival of high energy  $\gamma$ -ray photons. We provide an estimate for the time delay below (§2.2) after discussing a few basic results for a Poynting jet (§2.1).

### 2.1 Thomson photosphere and a few basic results for a Poynting jet

The energy-momentum (EM) tensor for a magnetic outflow is the sum of matter and electromagnetic parts. At a distance sufficiently far away from the central engine so that the magnetic field is in the transverse direction<sup>2</sup> and the thermal pressure is small, the EM tensor is given by:

$$T^{\mu\nu} = nm_p c^2 u^\mu u^\nu + \frac{1}{4\pi} \left[ \left( u^\mu u^\nu + \frac{1}{2} g^{\mu\nu} \right) B^2 - B^\mu B^\nu \right] \quad (1)$$

where  $n$  &  $B$  are number density of protons & magnetic field strength in jet comoving frame,  $u = \Gamma(1, v, 0, 0)$  is the 4-velocity,

<sup>2</sup> The transverse component of the magnetic field falls off as  $r^{-1}$  whereas the radial component as  $r^{-2}$ . Therefore, at a large distance from the center of explosion the transverse component of the magnetic field dominates.

$\Gamma$  is jet Lorentz factor,  $B^\mu = {}^*F^{\mu\nu}u_\nu = (0, 0, B_\theta, B_\phi)$  is the 4-magnetic vector,  ${}^*F^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}/2$  is the dual-electromagnetic tensor,  $F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$ , and  $A_\mu$  is 4-potential;  $(B_\theta^2 + B_\phi^2)^{1/2} = B$ .

The isotropic luminosity carried by the jet is given by

$$L = 4\pi r^2 T^{0r} = 4\pi r^2 \left( nm_p c^2 \Gamma^2 v + \frac{B^2 \Gamma^2 v}{4\pi} \right), \quad (2)$$

or

$$L = 4\pi r^2 nm_p c^2 v \Gamma^2 [1 + \sigma(r)], \quad (3)$$

where

$$\sigma \equiv \frac{B^2}{4\pi nm_p c^2}, \quad (4)$$

is the ratio of magnetic and baryon energy densities. The flux of baryonic mass (isotropic equivalent) carried by the jet is

$$\dot{M} = 4\pi r^2 nm_p \Gamma v \quad (5)$$

which should be independent of  $r$ . Making use of the expression for  $\dot{M}$  we can rewrite  $L$  as follows

$$L = \dot{M} c^2 \Gamma (1 + \sigma). \quad (6)$$

If radiative losses are small (radiative efficiency for observed  $\gamma$ -ray emission is  $\lesssim 50\%$ ) then

$$L \propto \Gamma(1 + \sigma) = \text{constant}. \quad (7)$$

It is easy to see from the equation for  $L$  that when the lab frame magnetic field strength ( $B\Gamma$ ) decreases with radius faster than  $r^{-1}$ , then the jet Lorentz factor increases with  $r$ . For magnetic field undergoing reconnection at a fraction of Alfvén speed (in jet coming frame)  $\Gamma$  increases as<sup>3</sup>

$$\Gamma(r) \sim (r/R_0)^\mu \quad \text{for } R_0 < r < R_{sat} \sim R_0 \sigma_0^3, \quad (8)$$

where  $R_0 \approx 10^7 \text{ cm}$  is the radius where the jet is launched, and  $\mu \approx 1/3$  for the case of reconnection in a striped-magnetic field configuration (Drenkhahn, 2002)<sup>4</sup>. The jet acceleration might be more complicated than represented by equation (8), and the acceleration might cease while  $\Gamma \ll \sigma_0$  as suggested by numerical simulations of highly magnetized jets eg. Tchekhovskoy et al. (2008), Komissarov et al. (2010). However, the recent work of Granot et al. (2011) also finds  $\Gamma \propto R^{1/3}$  after a brief initial spurt of acceleration when  $\Gamma$  attains a value  $\sim \sigma_0^{1/3}$ . From here on we shall assume that equation (8) is valid at least in a limited radius interval of the Thomson- and pair-production- photospheric radii.

Radiation can escape the jet when magnetic dissipation occurs at a radius larger than the Thomson photospheric radius ( $R_p$ ) which we calculate next.

The optical depth for photon-electron scattering is

$$\tau_T(R) = \int_R^\infty \frac{dr}{2\Gamma^2} \sigma_T n \Gamma. \quad (9)$$

We assume that there is one electron for every proton;  $\sigma_T$  is Thomson scattering cross-section. The particle density  $n$  can be expressed in terms of the luminosity ( $L$ ):

<sup>3</sup> We take the Lorentz factor of the jet at the base,  $R_0$ , to be of order unity since it is unphysical for the jet to be accelerated instantaneously to a high speed; Drenkhahn (2002) on the other hand takes  $\Gamma(R_0) = \sigma_0^{1/2}$ .

<sup>4</sup> Efficient acceleration of a Poynting jet can also proceed without reconnection as has been shown in a very nice recent work by Granot et al. (2011) who find the same scaling for  $\Gamma$  as in eq. 8.

$$n = \frac{\dot{M}}{4\pi r^2 m_p \Gamma v} \approx \frac{L}{4\pi r^2 m_p \Gamma c^3 \sigma_0}, \quad (10)$$

where  $\sigma_0 \equiv \Gamma(R_0)[1 + \sigma(R_0)]$ , and we have used equation (6) to replace  $\dot{M}$  in terms of  $L$ . Substituting equations (8) & (10) into (9) we find

$$\tau_T(R) = \frac{\sigma_T L R_0^{2\mu}}{8\pi(1+2\mu)m_p c^3 \sigma_0 R^{1+2\mu}}. \quad (11)$$

Therefore, the photospheric radius,  $R_p$ , corresponding to  $\tau_T(R_p) = 1$  is

$$R_p = \left[ \frac{\sigma_T L R_0^{2\mu} m_p^{-1} c^{-3}}{8\pi(1+2\mu)\sigma_0} \right]^{\frac{1}{1+2\mu}} = \left[ \frac{6 \times 10^{15} L_{52} R_0^{2\mu}}{(1+2\mu)\sigma_{0,3}} \right]^{\frac{1}{1+2\mu}} \quad (12)$$

where  $L_{52} \equiv L/10^{52} \text{ erg s}^{-1}$ ,  $\sigma_{0,3} \equiv \sigma_0/10^3$ , and we use cgs units for numerical values throughout the paper. For  $\mu = 1/3$ :

$$\frac{R_p}{R_0} = 1.4 \times 10^5 L_{52}^{3/5} \sigma_{0,3}^{-3/5} R_{0,7}^{-3/5} \quad (13)$$

The photospheric radius calculated above is modified due to creation of electron-positron pairs by photon-photon collisions. If one were to estimate the number density of  $e^\pm$  due to this process ( $n_\pm$ ) from the observed high-energy gamma-ray spectrum by assuming that all photons that have energy larger than  $m_e c^2$  in the jet comoving frame are converted to pairs as long as these photons are produced at a radius smaller than the pair-production photosphere (see §2.2) one would find that  $n_\pm$  is larger than  $n$  — the number density of electrons associated with protons (given by eq. 10) — by a factor  $\sim 50$ ; under this assumption  $n_\pm/\Gamma \sim n'_\gamma(> 1 \text{ MeV} * \Gamma)$  which is given by equation (16). However, this overestimates  $n_\pm$  by more than an order of magnitude due to neglect of an important negative feedback effect. As  $e^\pm$  pairs are created, the mean thermal Lorentz factor per charged lepton decreases as  $\sim (1 + n_\pm/n)^{-1}$  if particles are accelerated in shocks or as  $\sim (1 + n_\pm/n)^{-1/2}$  if particles are accelerated by electric field inside the current sheet produced by magnetic-reconnection. The consequence of this is that the peak of the spectrum ( $E_p$ ) shifts sharply to lower values thereby decreasing the number density of high-energy photons capable of pair production (see eq. 16), and that in turn reduces further creation of  $e^\pm$ . Thus, pair production is a self-limiting process and it does not allow charge-lepton density to be increased by more than a factor a few, and so the Thomson-photosphere radius given by equation (12) is not in error by more than a factor  $\sim 5$ ; this error in  $R_p$  contributes  $\lesssim 20\%$  error in the estimate of arrival time delay for high-energy  $\gamma$ -ray photons (see eq. 22)<sup>5</sup>.

A consequence of the pair production process (described above) is that the spectral-peak shifts to lower energies and the high-energy spectrum softens. Therefore, when the jet crosses the radius where the pair-production opacity drops below unity, high-energy  $\gamma$ -rays ( $> 10^2$  MeV) are able to escape conversion to  $e^\pm$ , and the spectral peak shifts to higher energies and the high-energy spectrum hardens. Fermi/LAT data shows that the arrival of high-energy photons is accompanied by these spectral changes, eg. Abdo et al. 2009a.

<sup>5</sup> If pair production were to change particle density by a large factor then we should see a big jump in  $E_p$  when the jet crosses the pair-production photosphere. Fermi/GBM sees a small increase to  $E_p$  a few seconds after the trigger, and that suggests that pair loading has a small effect on electron density.

## 2.2 Pair-production photosphere for a Poynting jet and the delay for the arrival of GeV photons

Consider a photon of energy  $E_0$  in observer frame. Its energy in the jet comoving frame ( $E'_0$ ), and the minimum photon energy ( $E'_\pm$ ) needed to convert this photon to an electron-positron pair are given by

$$E'_0 = (1+z)E_0/\Gamma, \quad E'_\pm \approx m_e^2 c^4 / E'_0, \quad (14)$$

where  $z$  is the GRB redshift, and  $m_e$  is electron mass. The comoving number density of photons of energy  $> E'_\pm$  —  $n'_\gamma(> E'_\pm)$  — can be calculated from the observed  $\gamma$ -ray luminosity,  $L_\gamma(E)$ . Let us consider the observed  $\gamma$ -ray spectrum to peak at energy  $E_p$ . The spectrum above  $E_p$  is a powerlaw function with photon index  $\beta$ , and the frequency-integrated-luminosity above  $E_p$  is  $L_{>p}$ , i.e.  $L_{>p} \equiv \int_{E_p}^\infty dE L_\gamma(E) \propto E_p^{2-\beta}$ . The comoving number density of photons with observer frame energy  $\geq E > E_p$ , at radius  $R$ , is given by

$$n'_\gamma(> E) = \frac{1}{4\pi R^2 \Gamma} \int_E^\infty dE \frac{L_\gamma(E)}{E(1+z)}. \quad (15)$$

Or

$$n'_\gamma(> E) = \frac{1}{4\pi R^2 \Gamma} \left( \frac{\beta-2}{\beta-1} \right) \left[ \frac{E_p}{E} \right]^{\beta-1} \frac{L_{>p}}{(1+z)E_p c}. \quad (16)$$

The optical depth for a photon of energy  $E_0$  to get converted to  $e^\pm$  while traversing through the jet starting from a radius  $R$  is given by

$$\tau_\pm(E_0, R) \approx \sigma_{\gamma\gamma} n'_\gamma(> E_\pm) [R/\Gamma], \quad (17)$$

where  $\sigma_{\gamma\gamma} = 6 \times 10^{-26} \text{ cm}^2$  is the photo-pair-production cross-section just above the photon threshold energy for producing  $e^\pm$ , and  $R/\Gamma$  is the comoving radial width of a causally connected region. Using equation (16) for comoving photon density, and equation (14) for  $E_\pm = \Gamma E'_\pm/(1+z)$  we find

$$\tau_\pm \approx \left( \frac{\beta-2}{\beta-1} \right) \frac{\sigma_{\gamma\gamma}}{4\pi R \Gamma^2} \frac{L_{>p}}{(1+z)^{3-2\beta} E_p c} \left[ \frac{E_p E_0}{\Gamma^2 m_e^2 c^4} \right]^{\beta-1}. \quad (18)$$

Substituting for  $\Gamma$  from equation (8) we find the radius  $R_{\gamma\gamma}(E_0)$  where  $\tau_\pm$  drops below unity so that photons of energy  $E_0$  are able to escape conversion to pairs —

$$\frac{R_{\gamma\gamma}(E_0)}{R_0} = \left[ \frac{\beta-2}{\beta-1} \frac{L_{>p} \sigma_{\gamma\gamma} E_p^{\beta-2} E_0^{(\beta-1)} R_0^{-1}}{4\pi c (m_e c^2)^{2(\beta-1)} (1+z)^{3-2\beta}} \right]^{\frac{1}{1+2\mu}} \quad (19)$$

For  $\mu = 1/3$  and  $\beta=2.2$ :

$$\frac{R_{\gamma\gamma}(E_0)}{R_0} \simeq 4.1 \times 10^6 L_{>p,52}^{0.41} E_{p,-6}^{0.08} E_{0,-4}^{0.49} R_{0,7}^{-0.41} (1+z)^{0.57}, \quad (20)$$

where  $E_{p,-6}$  is photon energy at the peak of the observed spectrum in units of 1 MeV &  $E_{0,-4}$  is the high energy  $\gamma$ -ray photon of energy in unit of 100 MeV for which the escape radius ( $R_{\gamma\gamma}$ ) is calculated.

Photons of energy less than about  $(R_p/R_0)^\mu/(1+z)$  MeV  $\sim 20$  MeV are not much affected by pair conversion considerations and we observe these photons essentially unattenuated whenever they are generated at a radius larger than the photospheric radius; for this estimate we used equation (13) for the photospheric radius  $R_p$ , took  $\mu = 1/3$ , and assumed that the spectral peak  $E_p \sim 1$  MeV. However, photons of energy  $\geq 10^2$  MeV are unable to escape until the jet has propagated to a much larger radius of  $R_{\gamma\gamma}$ .

The time it takes for the jet to propagate from  $R_p$  to  $R_{\gamma\gamma}(E_0)$ , as measured by the arrival of photons at an observer from these radii, is the observed delay for photons of energy  $E_0$ . This delay in observer frame,  $\Delta t(E_0)$ , is straightforward to calculate and is given by

$$\Delta t(E_0) = (1+z) \int_{R_p}^{R_{\gamma\gamma}(E_0)} \frac{dr}{2c\Gamma^2}. \quad (21)$$

Using equation (8) for  $\Gamma$ , the above integral reduces to

$$\Delta t \simeq \frac{R_0(1+z)}{2c(1-2\mu)} \left[ \left( \frac{R_{\gamma\gamma}(E_0)}{R_0} \right)^{1-2\mu} - \left( \frac{R_p}{R_0} \right)^{1-2\mu} \right] \quad (22)$$

We use equation (22) together with equations (12) & (19) to calculate the expected delay for the arrival of  $>10^2$  MeV photons (in comparison to photons of energy  $\lesssim 10$  MeV).

It should be noted that according to the reconnection model considered here the observed  $\gamma$ -ray luminosity is roughly proportional to the rate of dissipation of magnetic energy. The jet luminosity carried by magnetic fields is

$$L_B = B^2 \Gamma^2 R^2 v = L - \dot{M} \Gamma c^2 = \sigma \Gamma \dot{M} c^2 \approx L (1 - \sigma^{-1}), \quad (23)$$

where  $L$  is the rate of energy transport by the jet, and  $B$  is magnetic field in jet comoving frame. The  $\gamma$ -ray luminosity ( $L_\gamma$ ), when the jet is above the photosphere, can be calculated by estimating the total magnetic energy dissipated ( $\Delta E_B$ ) between radii  $R$  &  $2R$  during time interval  $\delta t \sim R/(2c\Gamma^2)$  – in observer frame – when the jet radius roughly doubles

$$\Delta E_B \sim R \frac{dL_B}{dR} \delta t \sim \frac{\mu L \Gamma \delta t}{\sigma_0}, \quad L_\gamma \sim \frac{\Delta E_B}{\delta t} \propto t^{\frac{\mu}{1-2\mu}}, \quad (24)$$

where  $t$  is time in observer frame. For  $\mu = 0.3$ ,  $\langle L_\gamma \rangle \propto t^{3/4}$  while the jet propagates between the photosphere and the radius where  $\Gamma(R) \sim \sigma_0$ , i.e. for  $1s \lesssim t \lesssim 4s^6$ ; The temporal behavior of  $L_\gamma$  on a longer time scale is governed by the activity of the central engine.

### 3 APPLICATION TO FERMI BURSTS

Fermi has detected 17 bursts with photons of energy  $>10^2$  MeV. Five of these bursts have redshift measurements and good photon statistics in the LAT band to determine accurately the delay for the arrival of  $>10^2$  MeV photons with respect to the Fermi/GBM trigger time<sup>7</sup>. For these bursts we carry out a comparison between the expected and observed delays.

A few basic properties of these five bursts are presented in Table 1. The table also contains the observed and the expected delays for each of these bursts. All of the expected delays, reported in the column marked  $\Delta t_{th}$ , were calculated for 100 MeV photons using the observed spectral peak ( $E_p$ ) and luminosity ( $E_{iso}/T_{90}$ ) for each burst.

<sup>6</sup>  $\langle L_\gamma \rangle$  is the average of  $L_\gamma$  which is subject to possibly large fluctuations due to central engine activity, stochastic magnetic reconnection and relativistic outflow produced in the layer where magnetic dissipation takes place.

<sup>7</sup> Two bursts – GRB 091003 & 100414A – were detected by LAT and have known redshift but these bursts do not show any measurable delays in the arrival of  $>10^2$  MeV photons and these are not considered in this work; the jet for these bursts, perhaps, might not be magnetic dominated or  $R_p \sim R_{\gamma\gamma}$ .

The theoretically calculated delay for the four long-GRBs for  $\mu = 1/3$  is smaller than the observed delays by a factor  $\sim 3$  (see Table 1). The expected delay has a very weak dependence on  $\gamma$ -ray luminosity ( $L_{>p}^{0.14}$ ),  $E_p$  &  $\beta$  (see equations 20 & 22). The delay depends primarily on  $\mu$ ,  $z$  and  $R_0$ ;  $\Delta t_{th}$  increases almost linearly with  $R_0$  &  $z$  and the dependence on  $\mu$  is very strong.

A factor of a few difference between  $\Delta t_{th}$  and  $\Delta t_{obs}$  could be due to the fact that  $R_0$  is a little larger than the value we have assumed for the calculations reported in table 1 for  $\mu = 1/3$ . If  $R_0$  were to be larger by a factor of  $\sim 2$  for long-GRBs and smaller by a factor  $\sim 3$  for short-GRBs then  $\Delta t_{th} \approx \Delta t_{obs}$ . The radius at which jet is launched ( $R_0$ ) depends on the mass of the central blackhole produced in these explosions, and it is not surprising that long- and short- GRBs leave behind blackholes of different mass.

The value of  $\mu = 1/3$  is motivated by the analytical results of Drenkhahn (2002) for jet acceleration via magnetic reconnection for an alternating-field configuration. The numerical results presented by Drenkhahn & Spruit (2002) — see fig. 1 — show that the average  $\mu$  might be a little bit smaller than  $1/3$ . Moreover, the value of  $\mu$  depends on the magnetic field geometry — whether the magnetic field gradient is larger in the radial or transverse direction (Drenkhahn 2002, fig. 3) — and therefore there is some uncertainty in regards to the precise value  $\mu$  might take for a Poynting jet. If we were to take  $\mu = 0.3$  instead of  $1/3$  (and  $R_0 = 1.5 \times 10^7$  cm) then the expected delays for long-GRBs are approximately equal to their observed values (see Table 1 – column marked  $\Delta t_{th}, \mu = 0.3$ ). However, for the short GRB (090510) the discrepancy is a factor 10 for  $\mu = 0.3$  &  $R_0 = 1.5 \times 10^7$  cm (table 1); this discrepancy disappears if we take  $R_0 \sim 10^6$  cm which might be reasonable for a short burst produced by a binary neutron star merger that gives birth to a blackhole of 2–3  $M_\odot$ .

For  $\sigma_0 = 10^3$  the radius where the magnetization parameter drops below unity, i.e. the magnetic dissipation becomes insignificant and jet acceleration ceases, is  $R_{sat} \sim R_0 \sigma_0^3 \sim 10^{16}$  cm. The pair-production photosphere radius ( $R_{\gamma\gamma}$ ) for the long-GRBs considered in Table 1 is  $\sim 10^{15}$  cm. Thus,  $R_{\gamma\gamma} < R_{sat}$  and the calculations presented in §2 are applicable to the GRBs considered in this paper.

We note that according to the Poynting jet model analyzed here the delay for the arrival of high-energy photons increases with increasing photon energy as  $\sim E_0^{0.17}$ . This can be used as a test of this model.

### 4 DISCUSSION

The external forward shock model for GRBs is in good agreement with the observed Fermi data for the high energy photons (energy  $\gtrsim 10^2$  MeV) after the prompt phase ( $t \gtrsim 30s$ ) as well as the x-ray, optical and radio data (Kumar & Barniol Duran, 2010). However, the external-forward-shock model cannot account for the high-energy data during the prompt phase if the fluctuations in the lightcurve are on a short time-scale (less than  $\sim 1s$ ) and are correlated with  $< 10$  MeV lightcurve. In this case one needs to look for another mechanism for generation of high-energy photons during the prompt phase that can explain the observed delay of a few seconds reported by Fermi for a number of GRBs (Abdo et al. 2009a; Abdo et al. 2009b). We note that it has been known for a long time that there is a slight time difference in the arrival of low and high-energy  $\gamma$ -ray photons of energy less than  $\sim 10$  MeV. However, when photons of energy less than  $\sim 10$  MeV are considered, it

GRB #	$E_p$ keV	$E_{iso,54}$ erg	$T_{90}$ s	$z$	$\Delta t_{obs}$ s	$\Delta t_{th} (\mu = 1/3)$ s ( $R_0=3 \times 10^7$ )	$\Delta t_{th} (\mu = 0.3)$ s ( $R_0=1.5 \times 10^7$ )
080916C <sup>1</sup>	424	8.8	66	4.35	4	2.3	4.7
090323 <sup>2</sup>	812	>3	150	3.57	~5	>1.2	>3
090510 <sup>3</sup>	3900	0.11	0.6	0.90	0.15	0.5	1.4
090902B <sup>4</sup>	726	3.7	22	1.82	2.5	0.8	2.2
090926A <sup>5</sup>	259	2.2	13	2.11	3	0.9	2.4

**Table 1.** GRBs detected by Fermi/LAT with known redshifts for which  $>10^2$  MeV photons are observed to arrive after lower energy  $\gamma$ -rays. 080916C, 090323, 090902B & 090926A are long-GRBs whereas 090510 is a short-GRB.  $E_p$  is the photon energy at the peak of  $\nu f_\nu$  spectrum,  $E_{iso,54}$  is the isotropic equivalent of total energy radiated in  $\gamma$ -rays in unit of  $10^{54}$  ergs,  $\Delta t_{th}$  is the theoretically calculated delay (using eq. 22) for the arrival of  $10^2$  MeV photons, and  $\Delta t_{obs}$  is the observed delay. We used  $\beta = 2.2$ ,  $\sigma_0 = 10^3$  &  $(\mu, R_0) = (1/3, 3 \times 10^7 \text{ cm})$  or  $(0.3, 1.5 \times 10^7 \text{ cm})$  for  $\Delta t_{th}$  calculations. **References:** (1) GRB 080916C:  $E_p$ ,  $T_{90}$  - van der Horst & Goldstein (2008),  $E_{iso}$  - Abdo et al. (2009a),  $z$  - Greiner et al. (2009); (2) GRB 090323 - Zhang et al. (2010); (3) GRB 090510:  $E_p$ ,  $E_{iso}$ ,  $T_{90}$ ,  $\Delta t_{obs}$  - Ackermann et al. (2010),  $z$  - McBreen et al. 2010; (4) GRB 090902B:  $E_p$ ,  $E_{iso}$ ,  $T_{90}$  - Abdo et al. (2009b),  $z$  - Cucchiara et al. (2009); (5) GRB 090926A:  $E_p$ ,  $E_{iso}$ ,  $T_{90}$ ,  $\Delta t_{obs}$  - Ackermann et al. (2011) & Zhang et al. (2011),  $z$  - Malesani et al. (2009).

is found that lower energy  $\gamma$ -ray photons lag higher energy photons (Norris et al. 1996), which is opposite to the result reported by Fermi for  $>10^2$  MeV photons. Thus, the observed delay in the arrival of  $>10^2$  MeV photons must have a distinct origin than that for lower energy photons.

A number of mechanisms have been suggested for this delay, eg. Razzaque et al. (2010), Asano et al. (2009), Toma et al. (2009), Vurm et al. (2011), Bošnjak et al. (2009), Daigne et al. (2011), Mészáros and Rees (2011).

We report in this work that the dissipation of magnetic fields in a Poynting jet model for GRBs offers a natural explanation for the observed delay in the time of arrival of photons of energy  $>10^2$  MeV. This delay arises because the Lorentz factor of a Poynting jet increases slowly with radius ( $\Gamma \approx R^{1/3}$ ) and as a result high energy photons are converted to  $e^\pm$  pairs even when they are produced far above the Thomson-photosphere radius ( $R_p$ ) whereas lower energy photons ( $E \lesssim 10$  MeV) can escape readily starting at  $R_p$ . A straightforward calculation shows (§2) that the delay for the arrival of  $>10^2$  MeV photons due to this process is similar to the observed value.

The recent work of Mészáros and Rees (2011) also considered a Poynting jet (with  $\Gamma$  varying laterally) for explaining the delay. However, according to them the diffusion of neutrons from the outer part of the jet to the faster-moving, inner part, and the resulting collisions between protons and neutrons were responsible for the generation of delayed GeV photons.

What we have shown here is that even without a neutron component to a Poynting jet the high-energy-photon delay can be understood — the acceleration and generation-of-radiation for a highly magnetized jet are coupled processes, and this offers a simple explanation for the observed delay.

The Poynting jet model described here predicts that the delay should depend primarily on  $R_0$ ,  $z$  (linearly) &  $\mu$ , and it has a weak dependence on high-energy photon energy ( $E_0^{0.17}$ ),  $E_p$  ( $\approx E_p^{0.05}$ ) &  $L_{>p}^{0.14}$ . If the average  $\mu$  does not vary from one burst to another (which is determined by the magnetic field topology of the jet) then one can use the delay in arrival of  $>10^2$  MeV photons to determine the product of burst redshift and  $R_0$ .

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